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A METHOD FOR ESTIMATING THE PROBABILITY OF DAMAGE FROM THE THER--ETC(U)
SEP 80 J S WICKLUND
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This report presents a method for rapidly estimating the probability of damage of an item from the thermal pulse of a nuclear detonation. The results can be displayed either as probability as a function of range for a variety of yields or as a range-yield plot for a given probability. Examples are given, using data on the ignition of fabrics and of common outdoor combustibles.

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1. INTRODUCTION

It has been difficult to estimate the range of thermal effects from a nuclear explosion because the transmission of thermal radiation through the atmosphere is strongly influenced by local weather conditions. Dense fog, rain, and falling snow strongly attenuate the radiation. On the other hand, the thermal radiation may be enhanced on a bright winter day because of scattering from snow on the ground and bright clouds overhead. These variations make the ranges of thermal effects difficult to predict unless the exact weather conditions are known.

If detailed data on the variations in local weather conditions are available, they can be exploited to yield the most probable levels of thermal radiation as functions of yield and distance. An excellent collection of such data for northwest Europe[1] contains various values of the atmospheric transmission factor as a function of range and the frequency of occurrence of these conditions. Frequency-of-occurrence curves are given for each month and for the year. Wicklund and Moore[2] manipulated the data on the yearly variations to give expressions for the probability that a given thermal level will be exceeded for any given range and yield, assuming a random time of detonation. Wicklund[3] uses one of these expressions to determine the probability of producing casualties from the thermal pulse as a function of range for any given yield. This report shows how the last technique can be extended to any item of military significance.

2. METHOD

Wicklund and Moore[2] developed the following formula to describe the probability, P, that a given radiant exposure, Q (cal/cm^2), will be exceeded at a distance R (km) from a burst of yield W (kT):

$$P\left\{\geq Q\right\} = \frac{1}{2}\left(1 - \text{erf}\,\frac{u}{\sqrt{2}}\right) \quad , \tag{1}$$

---

[1]*B. M. Cooke, Thermal Transmissivities for North-West Europe (U), Atomic Weapon Research Establishment AWRE 028/75 (July 1975). (CONFIDENTIAL)*

[2]*John S. Wicklund and Ralph G. Moore, Thermal Fluence from Nuclear Explosions: Effects of Local Weather Conditions and Delivery Errors, Harry Diamond Laboratories HDL-TR-1904 (June 1980).*

[3]*John S. Wicklund, Flash Burn Casualties from Nuclear Explosions: Effects for Skin Coloration and Burns under Summer Uniform, Harry Diamond Laboratories HDL-TR-1920 (September 1980).*

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where

$$u = \frac{\ln Q - \mu}{\sigma} \quad ,$$

with

$$\mu = \ln \frac{3.75W}{R^{2.67}}$$

and (2)

$$\sigma = 0.55 \; .$$

Equation (1) is a cumulative log-normal function. Its argument can be rewritten as

$$u = \frac{\ln \frac{QR^{2.67}}{W} - \ln 3.75}{0.55} \quad . \tag{3}$$

Equation (1) can be plotted in nomographic form,[2] using $X = QR^{2.67}/W$ as the independent variable in u. The result is figure 1: given Q, R, and W, it permits one to determine the probability that Q cal/cm^2 will be exceeded at R km for a W-kT burst. Since equation (1) comes from data obtained in northwest Europe, it is valid only for that region; hence, figure 1 also applies only to northwest Europe.

As an example of how to use figure 1, let us calculate the distance from a 35-kT burst at which there will be a 50-percent probability of igniting 8-oz/yd cotton khaki. The threshold for ignition for such fabric is 20 cal/cm^2 from a 35-kT weapon.[4] The 50-percent probability in figure 1 occurs at X = 3.75. Thus, $R^{2.67} = (3.75)(35)/20$, whence R = 2 km. Put another way, at a range of 2 km from a 35-kT burst, there is a 50-percent probability that 20 cal/cm^2 will be exceeded. This is the radiant exposure from a 35-kT weapon at which 8-oz/yd cotton khaki will ignite.

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[2]*John S. Wicklund and Ralph G. Moore, Thermal Fluence from Nuclear Explosions: Effects of Local Weather Conditions and Delivery Errors, Harry Diamond Laboratories HDL-TR-1904 (June 1980).*

[4]*S. Glasstone and P. J. Nolan, The Effects of Nuclear Weapons, Department of the Army Pamphlet 50-3 (March 1977), 286-8, §7.35.*

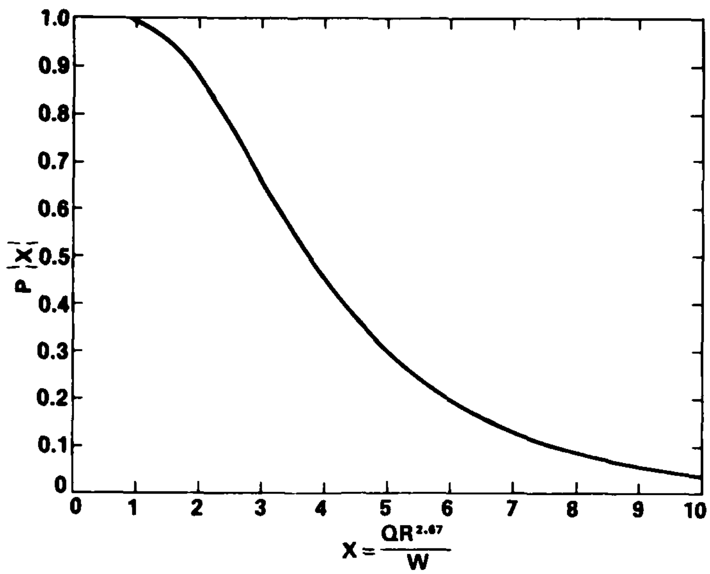

Figure 1. Nomogram for thermal flash in northwest Europe. Q is minimum expected radiant exposure (cal/cm^2), R is range (km), and W is yield (kT).

The radiant exposure necessary to produce a thermal effect is usually a function of the yield. The cotton khaki used in the preceding paragraph, for example, ignites at 30 cal/cm^2 from a 1.4-MT yield and at 39 cal/cm^2 from a 20-MT yield because the thermal pulse is broader for higher yields: it takes longer for the same amount of energy to be deposited in a substance. Thus, some of the energy can be lost by reradiation, conduction, or convection before damage occurs. This effect[4] is shown in table 1, columns 4 to 6. The ignition thresholds for various materials of military significance are seen to increase with increasing yield.

Since Q, which represents a damage threshold for the item being considered, can be expressed as a function of W, say, Q = f(W), equation (3) can be rewritten as

$$u = \frac{\ln R - \left(\frac{1}{2.67}\right) \ln \frac{3.75W}{f(W)}}{0.206} \quad . \tag{4}$$

[4] *S. Glasstone and P. J. Nolan, The Effects of Nuclear Weapons, Department of the Army Pamphlet 50-3 (March 1977), 286-8, §7.35.*

It was found that f(W) for the materials in table 1 could be expressed to better than 10 percent by the form $f(W) = aW^b$, where a and b are constants. These constants are listed in the final two columns of table 1.

TABLE 1. IGNITION THRESHOLDS FOR VARIOUS MATERIALS

Material*	Weight* (oz/yd)	Color*	Radiant exposure* (cal/cm^2)			$Q = aW^b$	
			35 kT	1.4 MT	20 MT	a	b
Clothing fabric							
Cotton	8	White	32	48	85	17	0.15
	8	Khaki	20	30	39	14	0.11
	8	Olive	14	19	21	11	0.06
	8	Dark blue	14	19	21	11	0.06
Cotton corduroy	8	Brown	11	16	22	7.4	0.11
Cotton denim, new	10	Blue	12	27	44	5.9	0.21
Cotton shirting	3	Khaki	14	21	28	9.5	0.11
Cotton-nylon mixture	5	Olive	12	28	53	5.2	0.23
Tent fabric							
Canvas (cotton)	13	White	13	28	51	6.0	0.21
Canvas	13	Olive	12	18	28	7.3	0.13
Outdoor tinder							
Deciduous leaves (beech)		Brown	4	6	8	2.7	0.11
Dry, rotted punk (fir)			4	6	8	2.7	0.11
Pine needles (ponderosa)		Brown	10	16	21	6.7	0.12
Fine grass (cheat)			5	8	10	3.4	0.11
Coarse grass (sedge)			6	9	11	4.3	0.10

*From S. Glasstone and P. J. Nolan, DA Pamphlet 50-3 (March 1977), tables 7.35 and 7.40.

3. APPLICATIONS

The method can be applied whenever there are suitable data on thermal damage. If there is only one data point on threshold and yield, figure 1 can be used to estimate the probability of damage as a function of distance from the burst point. With more data, a function f(W) is derived that can be used both for the computation of the probability of damage as a function of range for a given yield and for range-yield plots. The data in table 1 can be used for illustration since it is a convenient source of unclassified data with some military significance.

3.1 Computation of Probability of Damage as Function of Range and Yield

Equation (4) can be used directly in equation (1) to compute the probability of damage. A convenient way is to select a yield and to plot the probability of exceeding the threshold in equation (1) as a function of R. The results for the items in table 1 are plotted in figures 2 to 14 for yields of 10, 30, 100, and 300 kT.

Figures 2 to 10 illustrate the great ranges at which various fabrics ignite. These materials are used in uniforms, tents, and vehicles. At even greater ranges, troops can expect to suffer burns under a summer uniform;[3] at the ranges in figures 2 to 8, the fabric of the uniform itself can be expected to ignite.

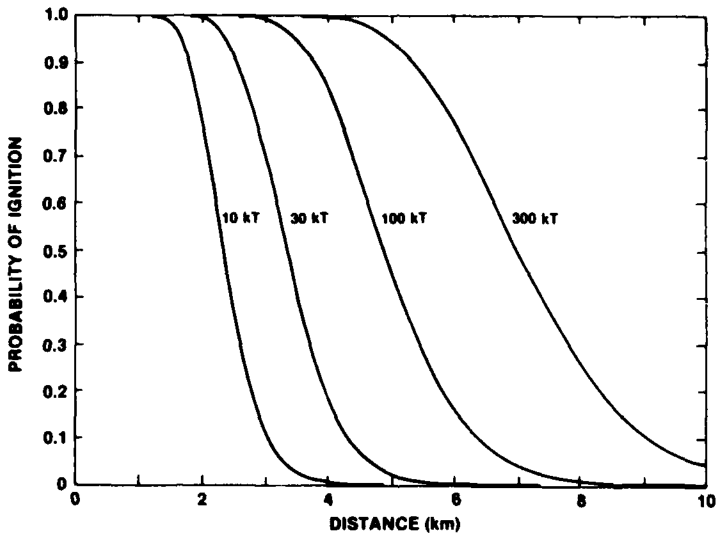

Figure 2. Probability that 8-oz/yd white cotton fabric will ignite.

[3]*John S. Wicklund, Flash Burn Casualties from Nuclear Explosions: Effects for Skin Coloration and Burns under Summer Uniform, Harry Diamond Laboratories HDL-TR-1920 (September 1980).*

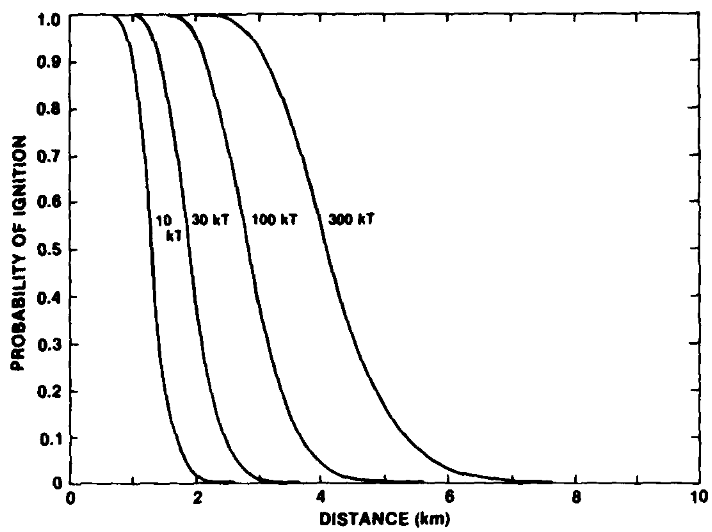

Figure 3. Probability that 8-oz/yd cotton khaki will ignite.

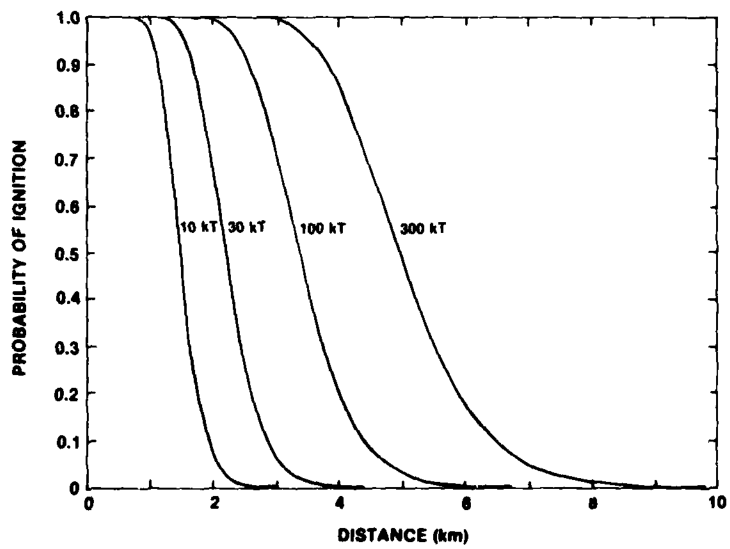

Figure 4. Probability that 8-oz/yd olive or dark blue cotton fabric will ignite.

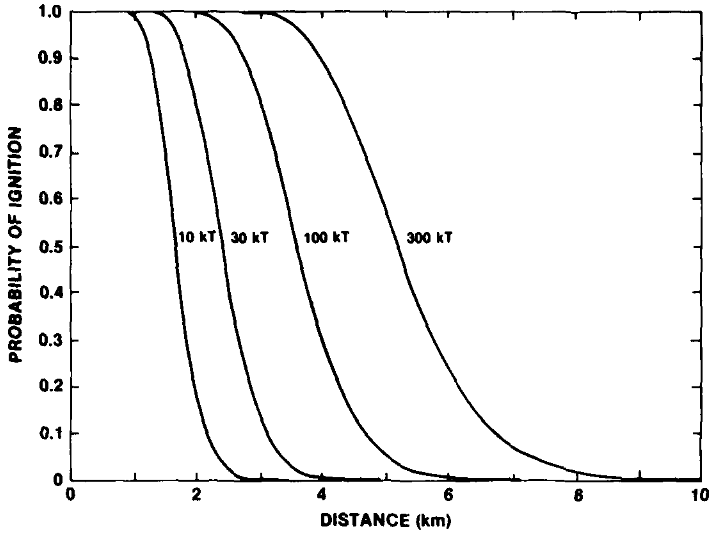

Figure 5. Probability that 8-oz/yd brown cotton corduroy will ignite.

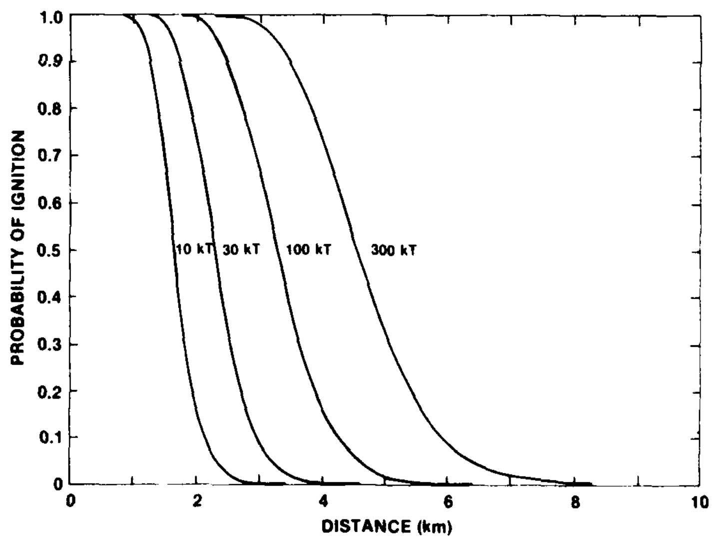

Figure 6. Probability that 10-oz/yd new, blue cotton denim will ignite.

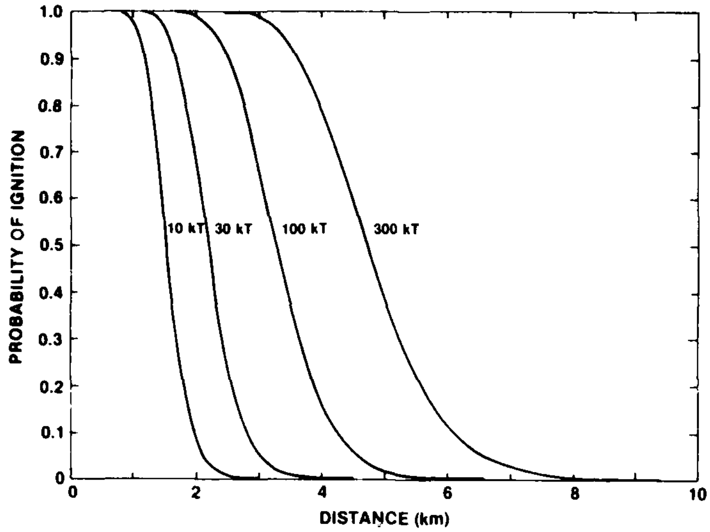

Figure 7. Probability that 3-oz/yd cotton khaki shirting will ignite.

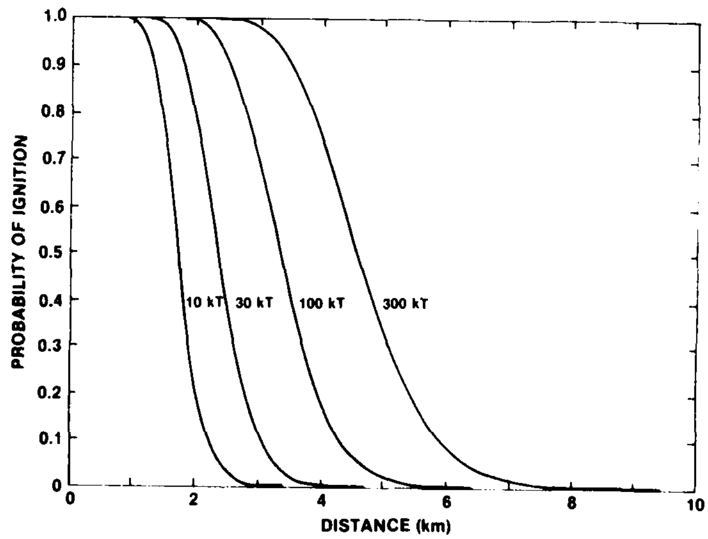

Figure 8. Probability that 5-oz/yd olive cotton-nylon mixed fabric will ignite.

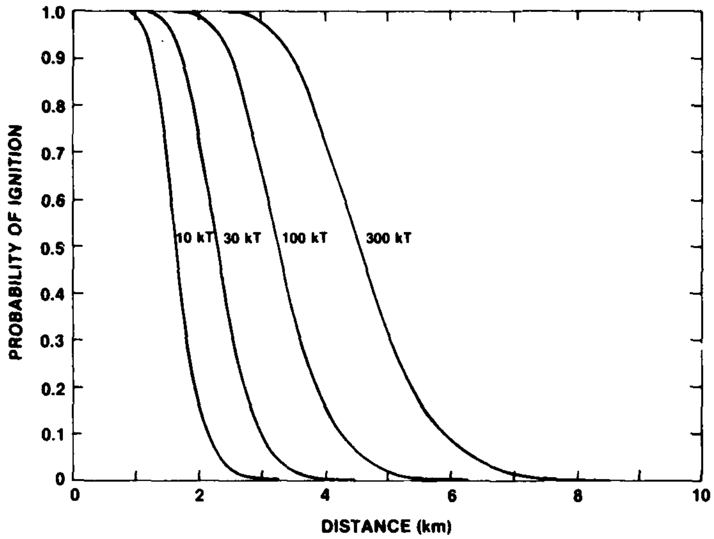

Figure 9. Probability that 13-oz/yd white cotton canvas will ignite.

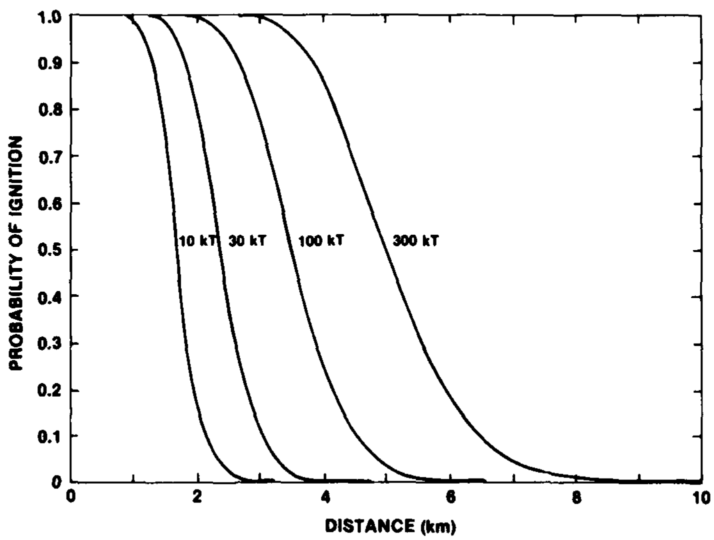

Figure 10. Probability that 12-oz/yd olive canvas will ignite.

Figures 11 to 14 illustrate the great ranges at which typical countryside and forest materials can be expected to ignite. Figures 11 and 12 illustrate some of the potential for the start of forest fires. Green leaves and pine needles can be expected to emit water vapor during the early stages of the pulse; this vapor inhibits the start of crown fires, except in periods of drought or for very close ranges. Gaps in the forest, however, can permit the thermal radiation to encounter forest debris and thus kindle a fire. Similarly, fields of grass or grain can be ignited, as shown in figures 13 and 14.

Figures 11 to 14 should not be taken too seriously since they represent a significant distortion of the method. Equation (3) was derived from data representing all possible variations of weather conditions. Clearly, anything out in the weather will be affected by it. Hence, while a covering of snow can permit the thermal radiation to be scattered to greater distances, it also affords an excellent shielding for forest debris. Grass and dead leaves retain moisture long after the rain has stopped; even though the atmospheric transmissivity improves after a storm, the ignition threshold is significantly greater. Thus, figures 11 to 14 certainly overestimate the actual probabilities of ignition.

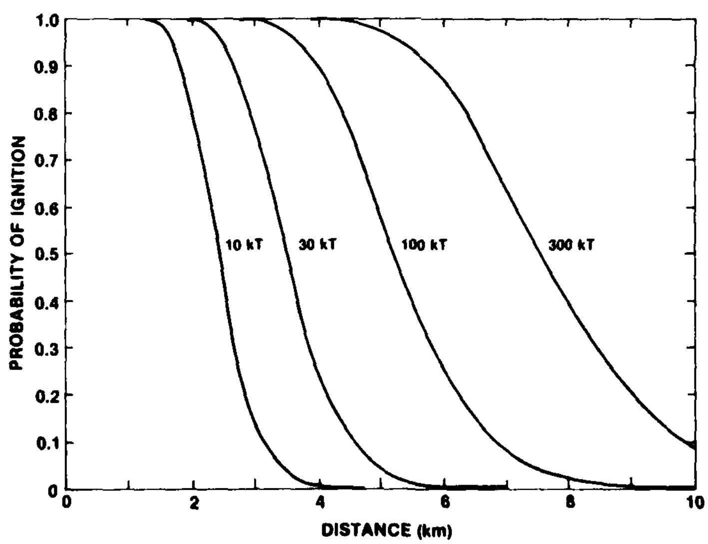

Figure 11. Probability that brown beech leaves or dry, rotted fir punk will ignite.

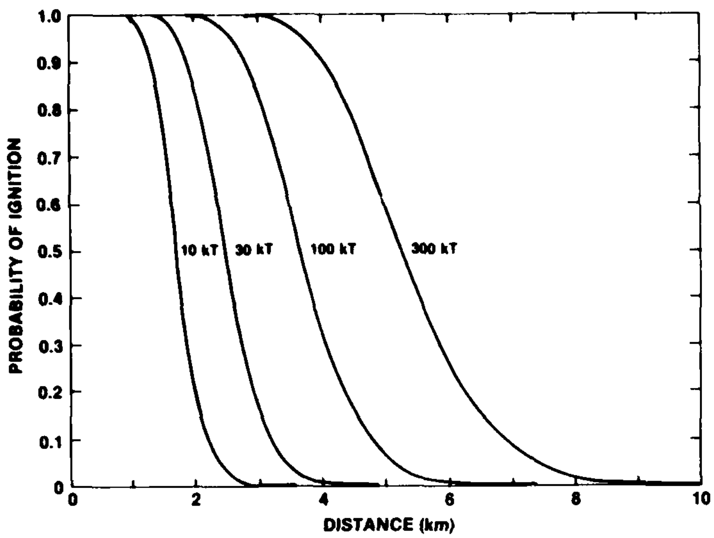

Figure 12. Probability that brown ponderosa pine needles will ignite.

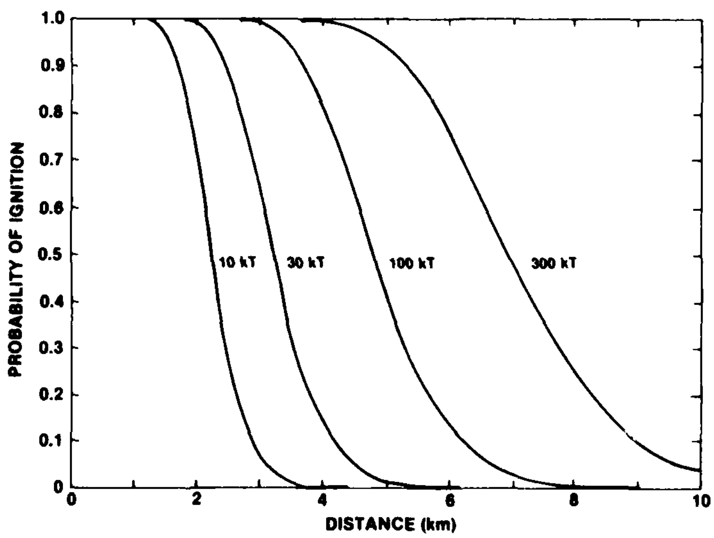

Figure 13. Probability that fine grass (cheat) will ignite.

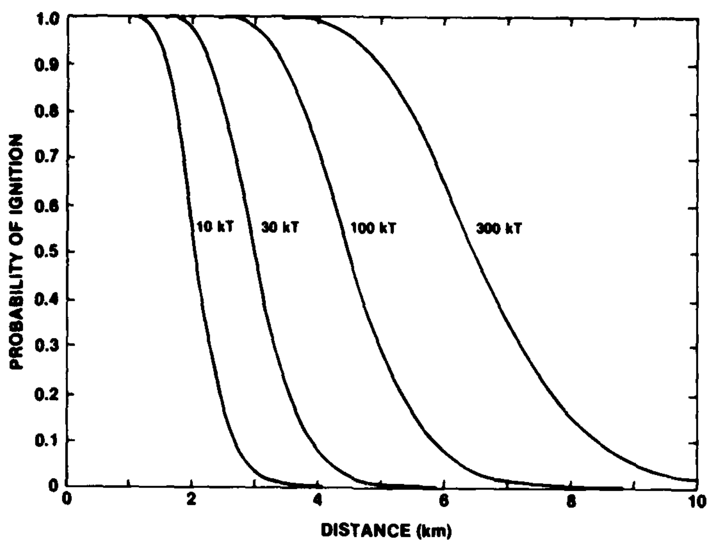

Figure 14. Probability that coarse grass (sedge) will ignite.

The same argument can be applied to figures 2 to 10, but it is not so relevant when applied to fabric. Soldiers tend to shake snow off their uniforms quickly and to protect themselves from rain. If dry clothing or drying fires are unavailable, their bodies serve as heat sources that hasten evaporation. Tents often contain heat sources that speed drying. Thus, figures 2 to 10 seem good approximations to reality.

3.2 Range-Yield Curves

Equation (4) can be used to produce range-yield curves for thermal damage to items of military importance. We select a suitable probability and derive expressions that relate the ranges and yields for that probability. One common practice is to take $P = 0.90$. This corresponds to $u = -1.28$ in equation (1). Rearrangement of equation (4) then gives

$$R = 0.768 \left[\frac{3.75W}{f(W)}\right]^{1/2.67} , \qquad (5)$$

which is the desired expression. Further simplification occurs if $f(W) = aW^b$, for then equation (5) can be written in the form $R = AW^B$, with $A = 1.26a^{-0.375}$ and $B = 0.375(1 - b)$.

Figure 15 shows such range-yield plots for the materials of figures 11 to 14. The caveats of section 3.1 are repeated. Many weapon effects vary as $W^{1/3}$. Substitution of the values of b from table 1 into the expression for B gives values remarkably close to 1/3. This closeness seems to be coincidental.

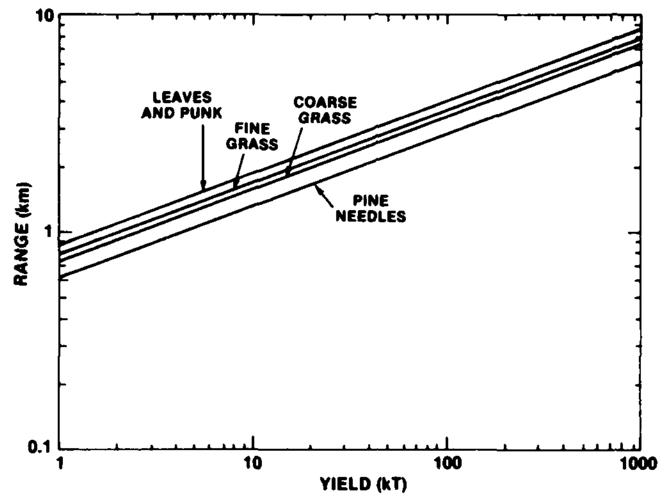

Figure 15. Range-yield plots for 90-percent probability that field and forest materials will ignite.

4. DISCUSSION

This report is about a method, not a panacea. As section 3.1 shows, the method must be applied thoughtfully. Where a body of data exists, it must be examined to determine whether it is immediately applicable; often, it is not. When experiments are designed, the applicability of the results to the method must be considered.

At times, the method should be modified to fit the circumstances. Were one to thoroughly investigate the fabrics used for illustrations in this report, probably only the results for canvas could be considered reasonably valid, for equation (3) comes from data that represent year-round variations in weather conditions. Presumably, lightweight fabrics would not be worn in the winter. For such a study, Cooke's data[1] for

[1] *B. M. Cooke, Thermal Transmissivities for North-West Europe (U), Atomic Weapon Research Establishment AWRE 028/75 (July 1975). (CONFIDENTIAL)*

summer must be averaged and then adapted by the technique of Wicklund and Moore[2] to obtain different constants for equation (3). (This adaptation would not be so difficult, for the complete analysis[2]--which includes weapon delivery errors--would not be necessary.) Similarly, data on outer winter garments should be used with a formula appropriate for winter.

Moreover, weather conditions differ throughout the world. It is probable that significant differences in range of effect will be observed among the several potential theaters of operations. If available, data of the same type as given by Cooke[1] should be compiled for each potential theater to determine whether there are such differences.

The results of calculations by this method are useful for any situation where weather is not specified. Given data on the response of an item to thermal pulses, quick estimates can be made of its vulnerability as a function of yield and range. If response data are lacking, it is sometimes possible to estimate a damage threshold from which vulnerability can be calculated.

---

[1]B. M. Cooke, *Thermal Transmissivities for North-West Europe (U)*, Atomic Weapon Research Establishment AWRE 028/75 (July 1975). (CONFIDENTIAL)

[2]John S. Wicklund and Ralph G. Moore, *Thermal Fluence from Nuclear Explosions: Effects of Local Weather Conditions and Delivery Errors*, Harry Diamond Laboratories HDL-TR-1904 (June 1980).

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